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Energy Procedia 76 (2015) 633 – 641

Energy

Procedia

European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

Quantifying induced effects of subsurface renewable energy storage

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Abstract

The geological subsurface offers large potential renewable energy storage sites through cavern or porous media storage systems. This work presents a methodology for assessing the size of the storage systems required, for modelling the storage operation and for predicting the induced effects and impacts on the environment by numerical simulations. The methodology is demonstrated for a hypothetical porous medium hydrogen storage and for geothermal heat storage. It is found that induced pressure effects may range over kilometers for gas storage, while temperature effects are limited to a few tens of meters for heat storage.

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Peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: energy storage, induced effects, parameterization, numerical simulation

1. Introduction

Due to greenhouse gas warming stemming from burning fossil fuels, as well as the finiteness of fossil fuel supply, the transition of energy supply from fossil sources to renewable energy sources is considered an option for mitigating climate change effects and preparing for a future of sustainable energy supply [1]. Additionally, Germany has decided to phase out nuclear energy production until 2022, which further accelerates the switch to renewable energy sources, in German termed “Energiewende”. Electricity generation from renewable sources has risen to ~28 % in 2011, while consumption of heat produced from renewable sources stayed constant at 10 % [2]. Renewable energy production is

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also strongly increasing in countries such as Denmark, Great Britain and the United States. However, due to the fluctuating nature of renewable energy sources such as wind power or solar power, energy storage will be required to dampen and compensate for times of non-matching supply, when not enough energy is generated. This energy storage will be necessary on different scales in terms of energy stored and the storage time to allow for short and long term balancing of the energy demand. Times may range from hourly to daily and seasonally, which requires storage options on all of these time scales [3]. Storage demand may reach the order of 50 TWh in Germany in 2050 [4]. When renewable energy production provides a large part of the total power generation, weather situations with periods of little wind and solar power have to be taken into account and be compensated for by excess production. For long term storage of large amounts of energy, arising from longer periods with excess wind or solar power, storage in the subsurface may potentially provide the large storage capacities required for storage on the daily, weekly or even seasonal time scale.

Potential storage options in the geological subsurface are mainly suitable for long term storage of large quantities of energy. Storage options include compressed air energy storage (CAES), which is also a short term (hour scale) storage option. In times of excess wind or solar power generation, the surplus electricity may be used to produce hydrogen gas by hydrolysis. Hydrogen gas may be stored in salt caverns or in porous media, such as depleted gas fields or saline formations. Hydrogen may also be used in a reaction termed the Sabatier process with carbon dioxide to produce methane (“Power to Gas”), which may either be directly supplied to the existing natural gas pipeline network or again be stored for later use in salt caverns or porous formations. For storage of natural gas, a large amount of long term experiences exists for porous formation and cavern storage. An overview of German subsurface gas storage capacities is given by [5], providing up to about 20 billion m³. Chemical conversion such as to hydrogen or methane offers a good possibility to store the large amounts of electric energy due to the higher energy densities, as e.g. compared to physical energy storage in hydropower plants or CAES. For details of these options see e.g. [6] or [7]. Surplus energy, which is either in the form of heat or is converted to heat, termed “Power to Heat”, may also be stored in the geological subsurface. For this end, methods and techniques from shallow and deep geothermal energy can be employed, such as borehole heat exchangers [8] or well doublets [9]. This applies to near surface storage of heat (or cold) from residential or industrial areas, but also to high temperature storage, considered here to cover temperatures up to 100°C in the subsurface, which may provide storage capacity for seasonal heat storage.

Although the geologic subsurface thus offers large storage capacities for geo-energy storage, also other types of subsurface are typically present. This includes mining, hydrocarbon retrieval, shallow and deep geothermal energy use, deposition of waste, fluid injections, nuclear waste disposal or carbon dioxide storage. Especially the use of near surface groundwater for drinking water or irrigation purposes as well as the interaction with the soil used for e.g. agriculture is of importance, as groundwater is a protected compartment by German law and any degradation of its condition is prohibited [10]. Any use of the subsurface for energy storage or exploitation reasons will result in induced effects. The effects induced may be roughly classified by the governing processes transmitting these effects. Thermal effects show through temperature changes, hydraulic effects through pressure changes or induced fluid movements, mechanical effects through uplift, subsidence or changes of the stress state and geochemical effects through induced reactions between pore water and rock as well as water quality changes. Effects may also interact, i.e. geochemical changes can be induced by a temperature pulse. These effects have to be accounted for during the planning and approving of geological energy storage sites, in order to ensure a reliable, safe and sustainable use of the subsurface. A prognosis and quantification of these effects can be supported by numerical simulation of the governing processes occurring during the storage operation. This however requires that these processes are identified, incorporated in the numerical models and their parameters known. The ANGUS+ project aims at providing the required data, models and methods to quantify these induced changes, to support a sustainable planning of the use of the geological subsurface [11]. Synthetic field sites are used to test the methodology and apply the models developed as steps towards an approach to subsurface planning of energy storage uses. For these, the storage efficiency and the induced effects have to be quantified. This approach is demonstrated in this paper for two examples, i.e. a porous medium gas storage as well as a near surface heat storage. For these two cases, some of the induced effects are investigated and their spatial extend is determined, in order to obtain the spatial demand of the individual storage option.

2. Induced effects, parameterization and model requirements

For a prognosis of the induced effects, they have to be identified and implemented in numerical models. For a porous medium gas storage the possible induced effects include mainly an induced overpressure in the storage formation, i.e. the sandstone layer used to inject the gas, when the gas storage is constructed. This pressure increase will lead initially to brine movement horizontally away from the injection location, which is dampened by the storage effect of the formation given by the compressibility or due to geological boundaries like sealing faults. Vertical pressure propagation may transmit the pressure increase to formations above or below the storage formation, i.e. the cap-rock. As a secondary effect, brine movement may be induced, which may rise to higher formations and could reach drinking water aquifers in cases of conductive pathways to these groundwater bearing formations. Increased pressure may also lead to rock deformation of and posing mechanical stresses to the geological storage formation or even formations above, causing for instance land rise or subsidence. The injected gas forms a fluid phase, which leads to effects like buoyant rise of the lighter stored gas phase and capillary trapping. A part of the total injected gas is not cycled during extraction and injection phases and serves as a cushion gas. This gas expands and compresses readily, thus dampening the pressure effects during the injection and extraction phases and ideally causing a spatially stable gas-water contact. Where the gas phase is present, the storage gas can dissolve in the formation water and potentially induce geochemical changes [12,13]. These depend on the type of storage gas, the composition of the reservoir fluid as well as the mineral composition of the formation rocks, potentially triggering effects like mineral dissolution and precipitation as well as pH changes.

For the second example of heat storage, induced effects are mainly transient temperatures, caused by the injection and extraction of heat through either borehole heat exchangers (BHE) or well doublets. Due to the temperature dependence of the reservoir water as well as the rock properties, many coupled phenomena arise. Changes in fluid viscosity and density may cause altered or induce fluid movement. Thermal expansion of the solid rock may cause changes in the stress field and induce rock movement. Because geochemical reactions are temperature-dependent via the equilibrium constants and the kinetic rate constants, geochemical changes and possibly alterations of the microbial activity are induced. These may alter the formation water composition by mineral precipitation or dissolution and also lead to pH changes [14]. In near surface aquifers, the injected heat is not only transported by conduction but possibly also by advection with the moving groundwater. This may cause the formation of heat plumes and thus enlarged regions of temperature alteration in the downstream direction.

For a quantification of these effects, numerical models are used in this work. Requirements for the numerical models are that they correctly represent the main induced physical effects. This is an important prerequisite, as otherwise a prognosis of the induced effects over the lifetime of such a storage operation is not possible. Therefore, so called THMC models, short for Thermal, Hydraulic, Mechanic and Chemical coupled models have to be employed, which is typically done in areas such as CO₂ storage or nuclear waste disposal [15, 16]. The suitability of codes like this for prognosis of induced effects has been shown in recent years especially for the topic of CO₂ storage, e.g. for examining large scale pressure responses [17] and for geochemical responses [18]. A series of related papers for CO₂ storage on the basis of the research project CLEAN is given by [19] and [20]. The code used in this work is the open source scientific code OpenGeoSys (opengeosys.org; [21]), which has been used for a number of subsurface research projects already [16, 22, 23]. For multi-phase flow simulations of the injected gas phase, the reservoir simulator ECLIPSE [24] is used. There is a number of other numerical models available, which can be chosen according to the relevant processes that need to be represented for the specific issue at hand.

Process based numerical simulation models require not only the correct representation of the governing processes but also adequate input parameters for the coupled processes induced in the subsurface. For the involved fluid phases, these parameters are e.g. the fluid densities, viscosities, heat capacities, heat conductivities and the phase composition, all as a function of pressure, temperature and chemical composition. For the rock phase, this includes e.g. parameters like intrinsic permeability, porosity, heat conductivities and capacities, compressibility and cohesion, surface area and mineral composition. Additionally, parameters representing both the fluid and the solid phase, like relative permeability, capillary pressure curves, wetting angle, surface tension, as well as a large number of geochemical parameters like phase equilibria and reaction rates are required. Fig. 1 shows a still incomplete listing of these parameters, sorted by induced effect and phase. The color code indicates the data availability. Fig. 1 shows that fluid related parameters are generally available, as they are measurable in the lab independent of field sites. Location or

formation specific data is typically rare and not directly available for the site in question. Parameters depending on both the fluid and the solid phase are typically not available for the storage gases.

Process	Phase	Parameter		Availability
Hydraulics (H)	fluid	fluid density	$\rho(p,T,C)$	
		fluid viscosity	$\nu(p,T,C)$	
	rock-fluid	hydraulic gradient	$\text{grad}(h)$	
		relative permeability	$k_r(S)$	
		capillary pressure	$p_c(S,\text{time})$	
		surface tension	σ	
		wetting angle	α	
	rock	permeability	$k_a,k_h(x,y,z)$	
		porosity	$n(x,y,z)$	
		rock density	$\rho(x,y,z)$	
Heat transp. (T)	fluid	heat conductivity	$\lambda(p,T,C)$	
		heat capacity	$c(p,T,C)$	
		thermal expansion	β_T	
		heat conductivity	$\lambda(x,y,z)$	
	rock	heat capacity	$c(x,y,z)$	
		heat dispersivity	$\alpha_{qph}(x,y,z)$	
Geomechanics	rock	elasticity module	$E(x,y,z)$	
		Poissons' number	ν	
		rock compressibility	κ	
		grain compressibility	κ	
		Biot's coefficient	b	
		cohesion	C	
component transport (C)	fluid	diffusion coefficient	$D_{aq}(T)$	
		solubility	$H(p,T,C)$	
		mol weight	MW	
		reaction rates	$K_{\text{react}}(C,T,?)$	
		fluid composition	$C_i(x,y,z)$	
		microbiolog. composition	$X_i(x,y,z)$	
	rock	tortuosity	$\tau(x,y,z)$	
		dispersivity	$\alpha_{qph}(x,y,z)$	
		grain diameter	$d(x,y,z)$	
		effective porosity	$n_e(x,y,z)$	
		mineral composition	$M_i(x,y,z)$	
		C _{org} -content	$C_{\text{org}}(x,y,z)$	

Fig. 1. Typical set of parameters required for a coupled THMC simulation of induced effects due to a subsurface energy storage operation. The color code indicates general data availability, with green indicating good availability, yellow case specific availability and red indicating little to no site specific availability of the required data.

3. Application example 1: Induced pressure effects of hydrogen gas storage in a porous formation

In the first application example, induced hydraulic effects of a porous medium gas storage operation using hydrogen as storage gas are quantified. The storage demand is estimated from the electricity consumption of Schleswig-Holstein, a state in North Germany with a population of about 2.8 mio. The state gets its electricity mainly from wind farms, making storage for dampening of the fluctuating energy production necessary. Assuming a period of one week with little to no electricity production from wind farms, 0.82 mio. GJ (228.11 GWh) of energy have to be stored [25]. The energy is stored as hydrogen gas in a porous formation, which is generated through electrolysis by using excess electricity in times of surplus energy production from wind power. Assuming an overall efficiency for the hydrogen re-electrification of 60 %, about 129 mio. m³ hydrogen gas have to be stored to compensate for a seven day calm for the whole state of Schleswig-Holstein [25]. Here a storage site covering about a quarter of that demand is considered.

The gas is stored in a partially eroded anticline in North Germany at about 500 m depth under typical trapping conditions (Fig. 2a). The reservoir rock is a sandstone of the Middle Rhaetian. The hydraulic properties permeability and porosity were assigned based on [26] and off-site data [27] to be 572 mD and 0.33 respectively. The gaseous hydrogen is injected and extracted through five wells, each fully penetrating the formation resulting in completions lengths of about 13 m. Target extraction and injection rates are 1,000,000 sm³/day/well for seven days and 150,000 sm³/day/well for 50 days, respectively, with a 30 day shut in phase in between. Rates are limited by minimum and maximum bottom hole pressures of 30 bar and 65 bar, respectively. Nitrogen is used as a cushion gas for the initial

fill, after that the hydrogen gas is cycled. Open boundary conditions for the fluid phases and compressibility of the fluid phases and the solid phase are assumed in these model simulations. More details on this site and the storage operation conditions used for the scenario simulations are given in [25]. In contrast to the work by [25] heterogeneous distributions of permeability, porosity, capillary pressure and relative permeability are used here, which are consistently correlated.

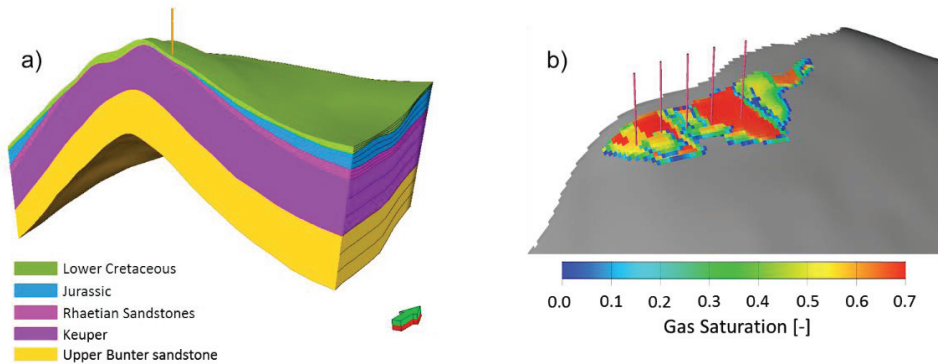


Fig. 2. (a) Geological setting of the Rhaetian sandstone formation in the partly eroded anticline structure. (b) Top view of the hydrogen gas saturation. Also shown are the five injection and extraction wells. The grey color indicates the reservoir brine. Well distance is about 400 m.

Fig. 2b shows the gas phase distribution at the end of a hydrogen injection cycle, when it is at maximum extent. It can be seen that the hydrogen gas is mainly restricted to the trap formed by the narrowing reservoir sandstone layer. However, some of it is moving a larger distance from the injection well, which will be lost as cushion gas. Saturations vary spatially due to the heterogeneous conditions assumed. It is found throughout two cycles of hydrogen injection and extraction that not all wells can operate at the target rates due to the heterogeneous conditions imposed with the average gas extraction rate being only 4.2 instead of 5.0 mio. sm^3/day .

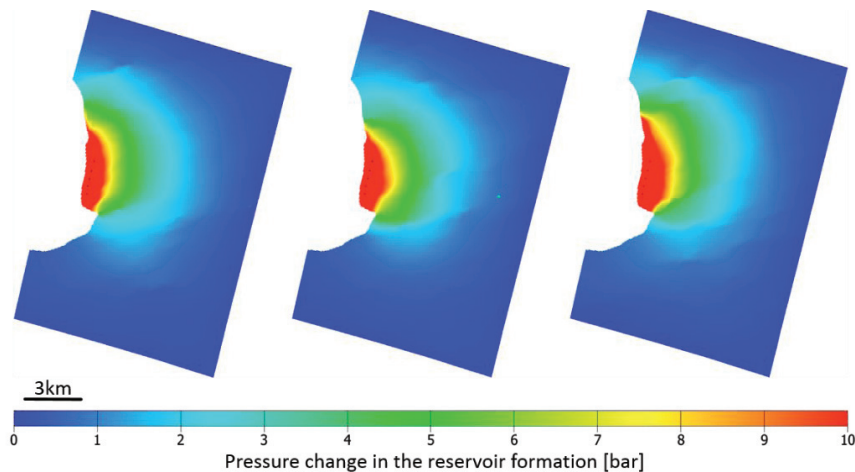


Fig. 3. Pressure increase relative to initial hydrostatic conditions at the end of the first injection period. Shown are results for three heterogeneous realizations in top view.

This model is used in a second step to assess the pressure effects induced during the storage operation. This pressure effect is largest at the end of the first injection period, as afterwards the hydrogen gas is cycled and thus pressure fluctuates in the same range. Fig. 3 shows the induced pressure increase in the reservoir formation at the end of the injection period. The formations above and below are considered impermeable for this simulation, which provides a worst case scenario for pressure propagation, as no dampening due to compression in these formations is accounted for. As can be seen, the pressure increase is decreasing strongly with increasing distance from the injection wells. The area with the highest pressure influence is the multiphase flow region near the wells, where pressure fluctuates between the specified bottom hole pressure bounds. Pressure change is becoming smaller than one bar for distances larger than about 7.5 km. This effect is seen very similarly in all 15 heterogeneous simulations performed, demonstrating that the exact distribution of the reservoir hydraulic parameters does not influence the far field pressure signal very much. This is, because areas of higher as well as lower permeability contribute to the pressure propagation on this scale. Thus pressure signals in the far field will be less sensitive to local hydraulic conditions and be more representative for the whole reservoir. The area affected by pressure increases of more than one bar is approximately 88 km². The individual wells show a dependence on local hydraulic parameters, as e.g. the injectivity is too low to allow for the target rate to be used. Also, close to the wells, the gas phase distribution will vary considerably. Under the conditions used here, the gas phase distribution varies locally in its spatial extent (see Fig. 2b); however, the overall affected area is similar in all realizations and in the order of 4.5 km².

4. Application example 2: Induced effects of subsurface heat storage

As second example, the storage of heat in the subsurface is considered. An array of coaxial borehole heat exchangers (BHE) is used to inject and extract heat from the ground. Each BHE is 100 m long and placed in a glacial till material, as is common in Northern Germany (see Fig. 4a). This material is of low hydraulic conductivity, so that heat transport is by conduction only and no heat is advectively transported away from the storage site. The BHE and the surrounding till are simulated using a high resolution model of the BHE, accounting for the pipes, pipe interior, grout and aquifer material separately and geometrically consistently. The model has been verified with experimental data for a single BHE [28] and is presented in detail in [8]. Parameters used are heat capacities of 4.18, 1.6, 3.0, 2.5 MJ/m³/K and heat conductivities of 0.56, 0.42, 1.5, 2.0 W/m²/K for working fluid, pipes, grout and aquifer, respectively. Heat storage is performed on a seasonal basis, with six months of heat injection by using an inlet working fluid temperature of 90°C, followed by six months of heat extraction using an inlet temperature of 1°C. All BHEs operate in parallel, using the same inlet temperatures and a working fluid flow rate of 2.5 l/s. Balancing input and output temperatures over the injection and extraction cycles, the storage site with 19 BHEs can store and retrieve up to 1.5 GWh of heat energy over the seasonal cycle. Efficiency increases with the number of BHEs used and rises up to 70 % for the 19 BHE storage site.

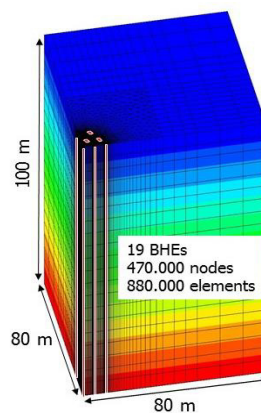


Fig. 4. Model set-up showing a quarter of the model area, symmetric to the front left edge.

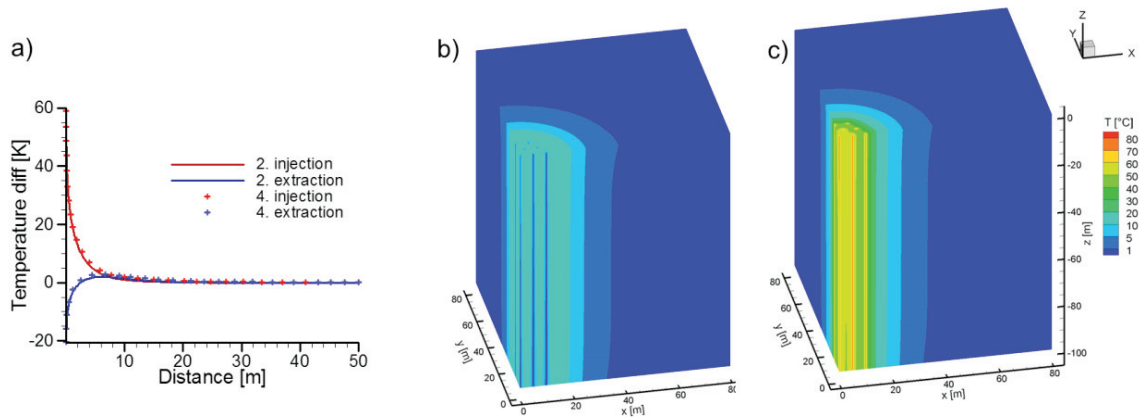


Fig. 5. (a) Temperature distribution around a single BHE at different cycles; (b) Temperature change at the end of the fourth heat extraction period; (c) temperature after the fourth heat injection period for the quarter model used in this work.

Fig. 5a shows the temperature distribution around an individual BHE at times during the different injection and extraction cycles. It can be seen, that the temperature is strongly changing close to the BHE, as temperature differences to the circulating working fluid are largest there. About 8 m from the BHE, a temperature maximum of about $+5^{\circ}\text{C}$ against background values is observable at the end of a heat extraction cycle. This shows, that some heat remains in the glacial till and is conductively moving away from the BHE with time. But this temperature peak also helps to keep temperatures high near the BHE in the next injection cycle, as temperature gradients are smaller and the heat flux away from the borehole is thus reduced. The spatial position of this temperature maximum is stable; however, the width is increasing slightly with each injection cycle, representing the amount of heat lost in the glacial till. Further away from the BHE temperatures drop to background levels, showing only slight increases at about 20 m distance. Fig. 5b and c show the temperature change for a heat storage site using 19 BHEs, placed at distances of 5 m, after the extraction and injection period, respectively. As can be seen, temperatures in the storage site are much higher now compared to a single BHE, since heat from the individual BHEs interacts and leads to higher temperatures up to 60°C in the storage. Heat from the outer BHEs is confining the heat from the inner BHEs, reducing the temperature gradient and thus the outward heat flux. Outside beyond the outer BHEs, temperatures drop quickly with increasing distance. Temperature increases of more than 5°C (10°C) are limited to distances of 14 m (9 m) from the next BHEs outside of the storage. Temperature increases of 1°C or more are restricted to a distance of 25 m from the next BHE or 35 m from the center of the storage site. The 1°C temperature change area does not significantly move between injection and extraction periods, showing a stabilization of the affected subsurface space. The area affected by such a storage site is thus approximately 0.004 km^2 .

5. Summary and conclusions

The two examples shown above demonstrate that for individual subsurface energy storage options induced effects can be obtained from simulation models of specific storage sites. For these, firstly energy use and energy storage scenarios for the energy demand over time and the energy supply to the storage have to be developed. This represents already a first obstacle, as for the large scale these numbers are highly uncertain, as they depend on future energy production methods, the increase in renewable energy production and overall efficiency increases in energy use. However, orders of magnitude estimations are obtained in this work, for dimensioning of the required storage capacities, which in turn determine the extent of induced effects. Induced effects for gas storage are mainly pressure effects due to the initial setup of the storage site, while the cushion gas dampens pressure fluctuations during hydrogen cycling. These pressure effects are on a large scale on the order of kilometers, thus affecting large subsurface areas. For heat storage, much smaller scales of affected subsurface space are involved, as temperature increase is restricted

to a few tens of meters around the storage site. However, the amounts of energy stored differ vastly between the storage options. The ratio of storage energy over affected subsurface area is about 2.6 GWh/km² for the hydrogen gas storage site if the pressure affected area is used and 50 GWh/km² if the gas phase affected area is used, and approximately 390 GWh/km² for the heat storage site at the high temperatures used here. The affected area per GWh energy stored is thus smaller for subsurface heat storage, which shows that this could be a viable option for larger scale storage of energy. While porous medium gas storage sites work well on the large scale, subsurface heat storage sites can work on a range of scales, if multiple BHEs are used.

Only the main induced effects are investigated in this work. Coupled processes will lead to more induced effects, as explained above. Future work will aim at quantifying these effects as well, in order to obtain a holistic description of the subsurface effects and processes and the spatial extend of these. This will ultimately enable an assessment of the spatial needs of the individual storage options and support a sustainable planning and use of the geological subsurface for energy storage.

Acknowledgements

The presented work is part of the ANGUS+ research project (www.angusplus.de). We gratefully acknowledge the funding of this project provided by the Federal Ministry of Education and Research (BMBF) under grant number 03EK3022 through the energy storage funding initiative "Energiespeicher" of the German Federal Government.

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